

# **Transition of Bayesian Expert System Model for Mine Burial to NAVO**

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Award Number: N0001404WX20354

<http://www7440.nrlssc.navy.mil/littoral%20dynamics>

## **LONG-TERM GOALS**

This work supports mine burial prediction by the US Navy by transitioning the capabilities provided by state-of-the-art, high-resolution process models to Naval operations. These models are synthesized by a statistical prediction tool (the Mine Burial Expert System—MBESM), which relates uncertainty in model input to uncertainty in the predicted mine burial. This work will produce more detailed and more accurate mine burial predictions and corresponding operational risk assessments.

## **OBJECTIVES**

This effort will facilitate the transition of the MBESM from the developers (JHU/APL) to the users (NAVO). Specific objectives in support of this goal include (1) evaluation the statistical and numerical implementation of the MBESM; (2) development of an objective definition of mine burial that includes a useful notion of risk; (3) development of a meaningful method to display predictions of mine burial and risk; (4) implementation of mine burial predictions over a map region; (5) comparison MBESM burial predictions to corresponding NAVO prediction; and (6) evaluation the predictive skill of the MBESM in an operational setting

## **APPROACH**

While the MBESM is ideally suited to the MBP problem, the present model requires further development before it can be applied in the NAVO setting. At present, the MBESM model computes sensitivities of predicted mine burial states to statistical variation in the inputs. This information is fed to the MBESM through synthetic, Monte Carlo simulations performed by Alan Brandt and Sarah Rennie at JHU/APL. The resulting prediction is a probability distribution function (PDF) that is information rich, yet too detailed and incompatible with NAVO's table lookup estimate, which provides a one-value prediction for each realization. Development is underway that to enable the MBESM to produce the requisite risk assessment.

The MBESM model originally assumed that perfect process-based sub-models and perfect PDFs have been used to provide information input. Since it is not likely that the sub-models or PDFs are perfect, ongoing work will allow the MBESM to estimate its own prediction errors. This information will be obtained from the process-based sub-model validation studies (work conducted by JHU/APL) and by gaining a better understanding of the input errors associated with data sets available to NAVO (work conducted by NRL).

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>SEP 2004</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2004 to 00-00-2004</b>	
4. TITLE AND SUBTITLE <b>Transition of Bayesian Expert System Model for Mine Burial to NAVO</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Naval Research Laboratory, Stennis Space Center,,Code 7440.3,, , ,</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>This work supports mine burial prediction by the US Navy by transitioning the capabilities provided by state-of-the-art, high-resolution process models to Naval operations. These models are synthesized by a statistical prediction tool (the Mine Burial Expert System???MBESM), which relates uncertainty in model input to uncertainty in the predicted mine burial. This work will produce more detailed and more accurate mine burial predictions and corresponding operational risk assessments.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>6</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

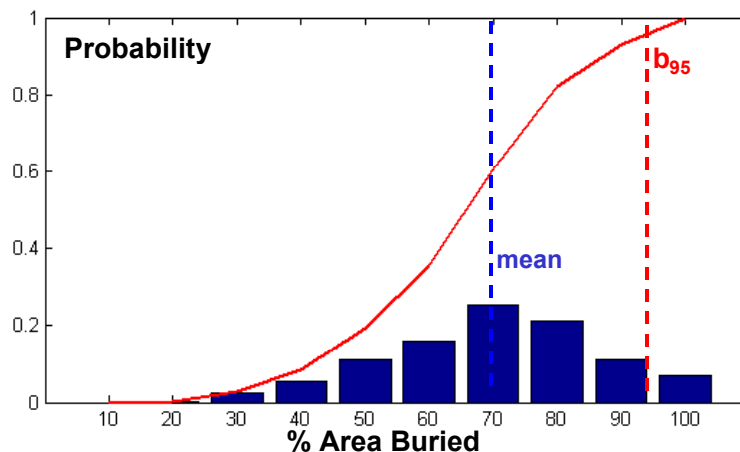
At present, the MBESM has “learned” mine burial dynamics from a particular suite of training realizations. Predictions for new realizations are obtained by manually entering data. Typical NAVO operations consist of up to 1 m<sup>2</sup> resolution over several km<sup>2</sup> map regions, yielding perhaps O(10<sup>6</sup>) realizations. The present MBESM is not capable of generating map area predictions that are compatible with NAVO predictions. The MBESM needs to be modified in order to allow direct comparison with existing NAVO methods and some trial map regions need to be analyzed and compared to typical NAVO predictions. This work will be implemented by NRL.

## WORK COMPLETED

To date this effort has achieved the following accomplishments: (1) revision of the Technology Transition Agreement between NAVO and ONR; (2) review and modification of the MBESM scientific and technical implementation details; (3) development of the JAVA-API interface; (5) development of methodology to pass known sub-model uncertainties (i.e., errors in parameterizations of physical processes) to the MBESM; (6) implementation of the impact burial portion of the MBESM using data supplied by NAVO; and (7) comparison the MBESM mine burial prediction to the corresponding NAVO Mine Burial Prediction.

## RESULTS

To be operationally useful, the MBESM must make predictions that are compatible with existing Navy procedures. The predictions under the current doctrine fall into one of five categories of percent mine case burial: 0%, 1%-10%, 10%-20%, 20%-75%, and 75%-100%. The variable width of the prediction categories attempts to account for the uncertainty in the knowledge used to make the prediction. However, the doctrinal procedure is incapable of adapting to different levels of input uncertainty and does not provide a method for balancing the associated operational risks. Instead, the MBESM can predict probability in more highly-resolved burial classes, which were implemented in equally-spaced 10% intervals (Figure 1).



**Figure 1. Burial probability distribution using the MBESM impact model.**  
*[PDF indicates that the burial percentage increases as the risk decreases. The predicted mean burial is 70%, while 90% burial is associated with 5% risk (b<sub>95</sub>).]*

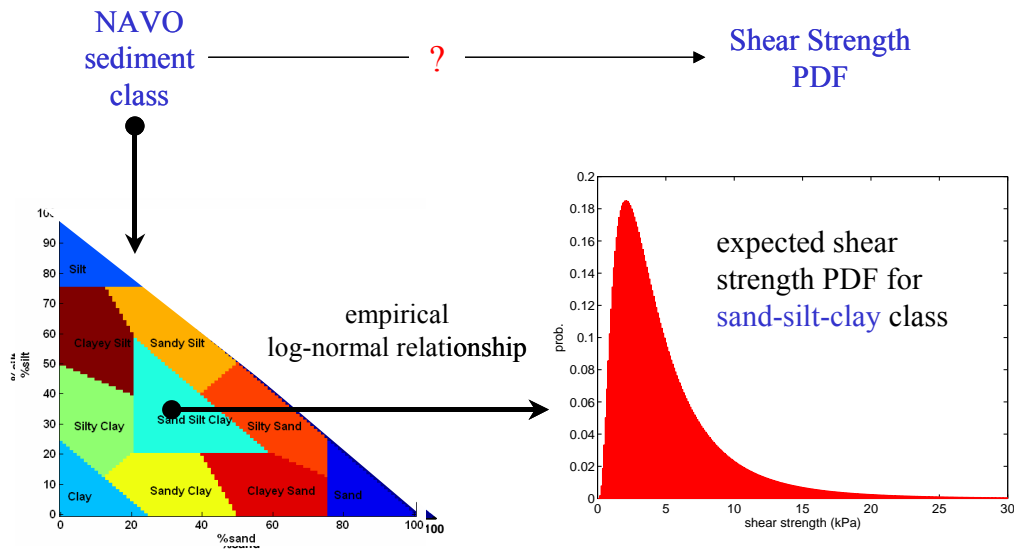
In operational use, a risk threshold is specified. Then, mine burial must be reported in a manner consistent with the risk. We define risk as the probability that a mine will be buried more than  $b(\alpha)$ :

$$\text{Prob. [ burial } < b(\alpha) ] = \alpha \quad (1a)$$

and

$$\text{Risk} = 1 - \alpha. \quad (1b)$$

For instance, a conservative risk might be  $\alpha=95\%$ , indicating that the prediction is allowed to fail (i.e., burial is greater than predicted) only 5% of the time. Figure 1 shows an example where the MBESM was run with a single set of inputs, each of which was known with certainty within the assigned input bin categories. The output shows the probability of burial for each of 10 possible states. The example illustrates that even when the inputs are known with high certainty, there can be a great deal of uncertainty in the resulting MBP (which is due to model sensitivity to small variations in the input). The most likely burial is the mean value (70% burial in this case), but there is significant probability of greater burial. The prediction that allowed 5% risk was one of 90% burial. The utility in coupling risk and burial is that a user is free to specify the risk and the MBESM result is interpreted to produce a consistent measure of burial.



**Figure 2. Mapping between sediment class and shear strength PDF**  
*[Schematic diagram shows that a NAVO sediment class maps to a particular range of sand-silt-clay percentages and these percentages are used to compute a shear strength PDF]*

In order to produce burial predictions, probability distributions of required inputs are required. This posed a particular hardship for estimating bed shear strength, since NAVO databases did not typically contain this information directly. This problem was solved by assuming that the bed shear strength could be estimated if the sand and clay content of sediments were known. The spatial distribution of sediment type was available from standard Navy databases (Figure 2), and the sand/clay content of

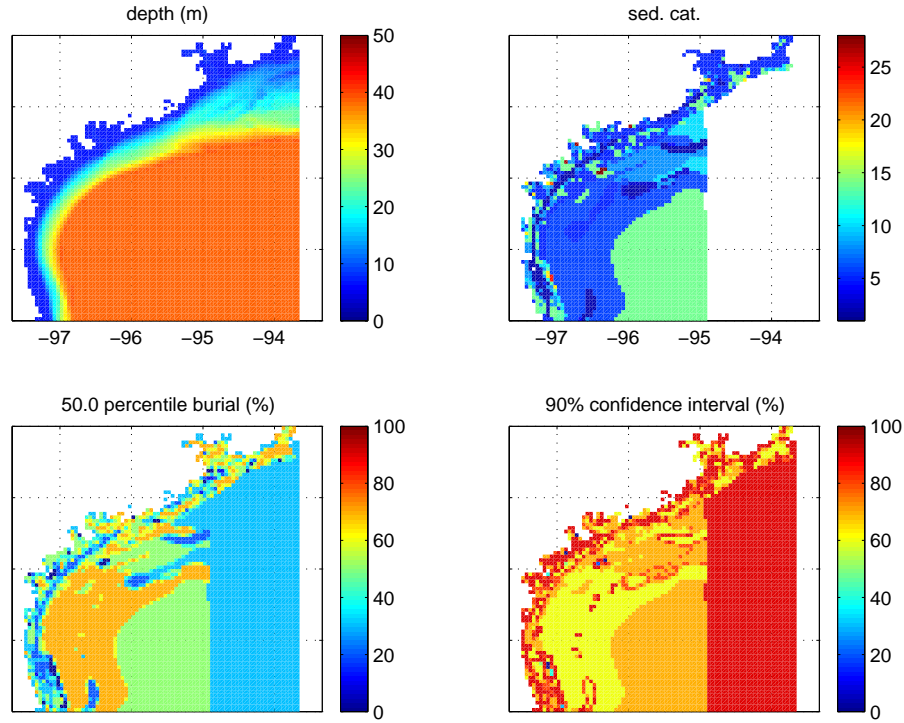
these classes was known. An empirical formula (equation 1) converts the sand/clay content ( $c_{sand}, c_{clay}$ ) to a distribution of shear strengths, based on a log-normal distribution:

$$\hat{S}_u = \exp[0.5\sigma_{ln}] \exp[\hat{\beta}_{sand}c_{sand} + \hat{\beta}_{clay}c_{clay}] \quad (2a)$$

and

$$\sigma_{Su}^2 = (\exp[2\sigma_{ln}] - \exp[\sigma_{ln}]) \exp[2(\hat{\beta}_{sand}c_{sand} + \hat{\beta}_{clay}c_{clay})], \quad (2b)$$

where  $S_u$  and  $\sigma_{su}$  are the mean and standard deviation of shear strength,  $\sigma_{ln}$  is the standard deviation of the residuals of the log-transformed data, and  $\beta_{sand}, \beta_{clay}$  are empirical coefficients describing the dependence of shear strength on sand/clay content. The resulting shear strength PDF is used as input to the MBESM.



**Figure 3. Mapped display of MBESM inputs (depth, sediment classification) and outputs (burial percentages and confidence).**

*[There is a 50% probability of exceeding the mapped 50<sup>th</sup> percentile burial level. (E.g., in the orange region, there is a 50% probability that at least 70% of the mine case will be buried.). The confidence interval indicates the range of burial that encompasses 90% of the probability. (E.g., in the region with no sediment data, 90% of burial probability is spread over 90% of all burial states.)]*

The MBESM was applied to a large exercise area (Figure 3), and burial associated with, in this case, 50% risk were computed. The spatial structure of the burial map, indicated the strong dependence of

burial on sediment type. Note that the uncertainty map copes with regions where data are missing (indicating that the entire 0-100% burial range could be encountered there). Regions with large uncertainty can be used to indicate where more data should be collected.

## **IMPACT/APPLICATIONS**

This work demonstrates that, even with present, sub-optimal inputs, the MBESM is capable of making burial predictions that are consistent with Navy operations. In order to achieve this goal, the methodology demonstrates a clear impact on how basic research results and data collection must be treated in order to be compatible with ANY attempt to quantify environment-dependent operational risk. First, uncertainty associated with model errors must be revealed to the subsequent statistical analyses. In this case, the empirical formulation in equation 2a (a prediction of shear strength) required the corresponding uncertainty formulation (equation 2b) in order to fully specify the input uncertainty as, in this case, a log-normal distribution. Second, uncertainty associated with data inputs must be retained. In our case, the broad range of actual sediment properties (i.e., %sand,%clay) indicated by the NAVO classification system served this purpose.

## **TRANSITIONS**

The MBESM (developed by JHU/APL) and associated add-ons developed by NRL currently run on NRL computing systems. The purpose of this arrangement is allow NRL to emulate NAVO's operational setting, while precluding any computational burden placed on NAVO. Once the MBESM and its add-ons are fully functional at NRL, we intend to physically transitioned the software to NAVO computers.

## **RELATED PROJECTS**

This work is part of ONR's Mine Burial Prediction program (<http://www.mbp.unh.edu>).

## **PUBLICATIONS**

Plant, N.G., and P. Fleischer, The operational use of risk in mine burial prediction, in *Sixth international symposium on technology and the mine problem, may 9-13, 2004*, Melody Burgess, Monterey, California, 2004.

Rennie, S., A. Brandt, and N. Plant, Utilization of an expert system for predicting mine burial: Quantifying uncertainty, in *Sixth international symposium on technology and the mine problem, may 9-13*, Melody Burgess, Monterey, California, 2004.

Abelev, A.V., P.J. Valent, N.G. Plant, and K.T. Holland, Evaluation and quantification of randomness in free-fall trajectories of instrumented cylinders, in *Proceedings, oceans 2003*, 2004.

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